Eddy Current Calculation of Solid Components in Fractional Slot Axial Flux Permanent Magnet Synchronous Machines

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***Abstract*—This paper presents the study of an axial flux permanent magnet (AFPM) machine with a novel structure, which consists of the segmented stator teeth and concentrated winding, with one rotor and double stators. MMF with large harmonic components cause eddy-current losses in PMs, and Significant eddy-current losses in the PMs will not only affect the machine efficiency, but may also result in excessive heating, which could lead to irreversible deterioration in the machine performance. The machine has been analyzed by three dimensional finite element analysis (3D FEA). Eddy-current losses in PMs, PM holder and solid-iron stator yoke were analyzed by time-stepped 3D FEA. Analytical method was also developed to calculate the eddy-current loss of PMs and PM holder versus speed at no-load condition. The calculation result was compared with time-stepped 3D FEA of model with laminated stator yoke, achieving good agreement.**

I. INTRODUCTION

Recently, axial flux permanent magnet machine (AFPM), which have unique characteristic such as high torque density, and excellent efficiency, are popular for various applications such as electric ship, electric vehicle, and airplane propulsion due to its compact construction and high power density [1-3]. The fractional slot, concentrated winding has shortened end windings compared with that with a distributed winding, low power losses and shorter radial lengths, but the magnetic motive force (MMF) has large harmonics [4]. AFPM with fractional slot, concentrated windings have been investigated in literature [5,6]. Soft magnetic composite (SMC) was used for stator core in [5] for its simple fabrication comparing with axial laminated steel cores, which normally cannot be easily made by stampings, however, SMC material is expensive and the permeability is low compared with laminated steel. The machine proposed in [6] has a novel segmental laminated steel stator, the back-emf and cogging torque were investigated.

In this paper, an inner-rotor double-stator AFPM with 18 slots per stator and 16 poles was analyzed, emphasizing on permanent magnet (PM) overhang and eddy-current losses. The machine was designed for 3 kW wind generator. The inner-rotor type structure with two stators was given in Fig. 1. The concentrated winding composed of individual coils wound on teeth, and the teeth were then inserted to stator yoke. PMs are fixed to PM holder and guider on rotor, which are made of stainless steel.

Eddy current losses in the rotor permanent magnet are caused by three different reasons. A concentrated winding stator produces a large amount of current linkage harmonics generated flux densities travelling across the permanent magnets, thereby causing eddy currents, namely winding harmonics. Secondly, the large slot opening causes flux density variations that induce eddy currents in the permanent magnet, namely permeance harmonics. Finally, frequency-converter-caused time harmonics in the stator current waveform cause extra losses in the rotor.

II. RESULTS

Significant eddy-current losses in the PMs will not only affect the machine efficiency, but may also result in excessive heating, which could lead to irreversible deterioration in the machine performance, for instance demagnetization of the magnets. Eddy-current losses also occur in the magnet holder, which is made of conducting material. In this part, machine was simulated by time-stepped 3D FEA at no-load and full-load condition using commercial software JMAG to study eddy-current losses in solid electric conductive regions first, and analytical analysis was used to calculate eddy-current loss in rotor at variable speed. The eddy-current density of solid iron stator yoke was plotted in Fig. 2, which shows that the flux density at stator yoke is high for solid iron stator yoke to generate eddy-current. Eddy-current density distribution of rotor was plotted in Fig. 3, showing that area under slot opening has high density, PM holder at outer radius also suffers from eddy-current loss.

The eddy-current losses in rotor at no-load and full- load were compared in Fig. 4. MMF with large harmonic components at full-load would cause eddy-current losses in PMs, and air-gap permeance variation due to slot slotting is neglected in [7]. However, research carried out in this study found that eddy-current loss is only slightly increased (from 31.9W to 33.8W) in PMs at full-load generating operation, whereas nearly two times (from 7.2W to 13.9W) in PM holder. This is due to that although MMF harmonics increases eddy-current losses, load current at generating operation has negative component in direct-axis, reducing flux density at air-gap, whereas PM holder suffers more from MMF harmonics. The developed analytical method has been used to calculate the eddy-current loss of PMs and PM holder versus speed at no-load condition. The calculation result was compared with time-stepped 3D FEA of model with laminated stator yoke as shown in Fig. 5 achieving good agreement.

TABLE I
DESIGN SPECIFICATIONS AND DIMENSIONS

Specifications		Rotor dimensions	
Rated output power	3kW	Poles	16
Rated voltage	250V	PM thickness	8.4mm
Frequency	32Hz	Outer diameter	334.4
Speed	240rpm	Inner diameter	70mm
		Pole arc ratio	0.7
Stator dimensions		Overhang length	5mm
Outer diameter	310mm		
Inner diameter	110mm	Permanent magnet specification	
Slots	18	Material	Nd-Fe-B
Coil turns	110turns	Coercively	890kA/m
Coil diameter	1.1mm	Remnant flux density	1.2T
Slot insulation	1.5mm	Winding connection	2-Y

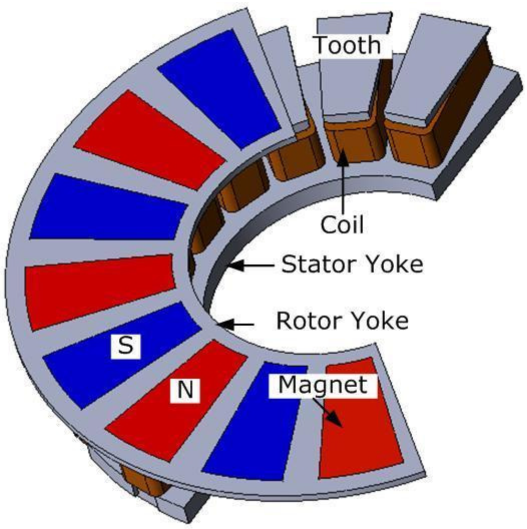

Fig. 1. Structure of inner-rotor type AFPM

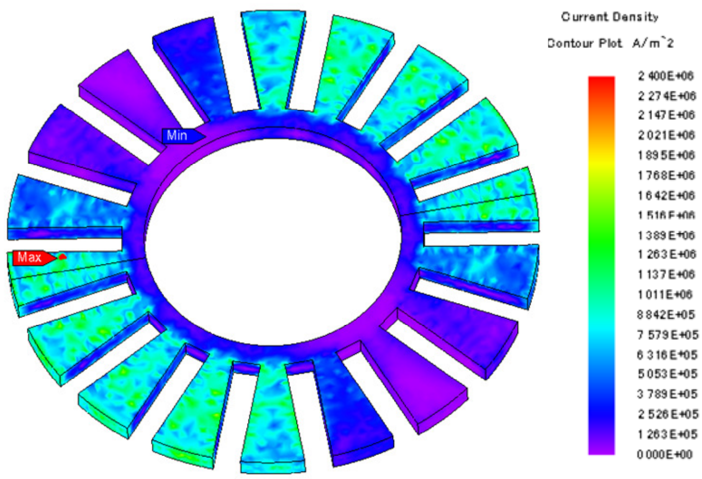

Fig. 2 Plot of eddy-current density in solid stator yoke.

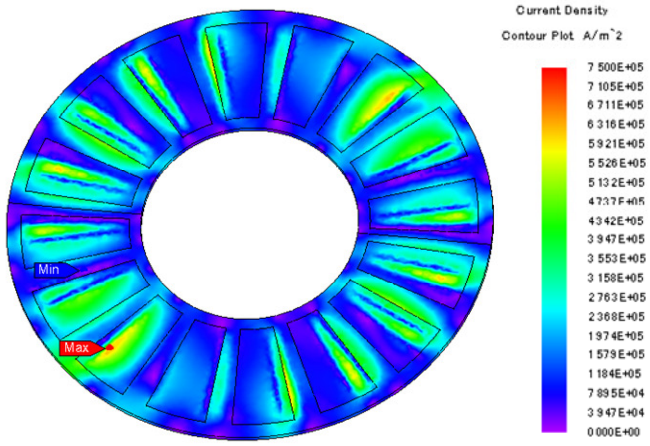

Fig. 3 Plot of eddy-current density of rotor.

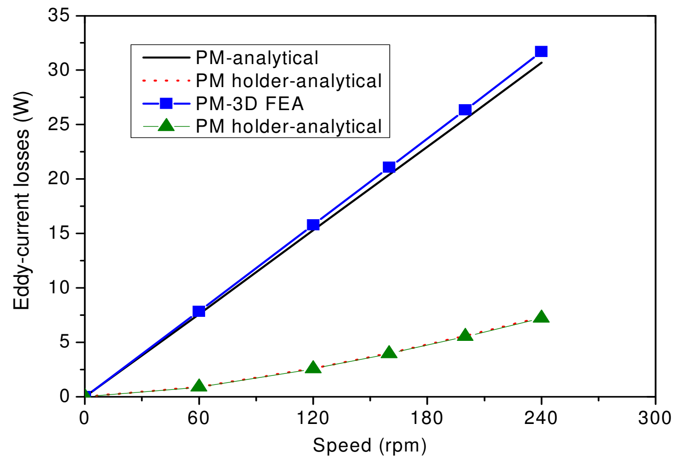

Fig. 4 Variation of eddy-current losses with rotor speed at no-load.

III. REFERENCES

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